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Low Cost Phased Arrays

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13. ABSTRACT (*Maximum 200 words*)

In a phased array antenna the phase shifters (or T/R modules in active aperture phased arrays) with their beam steering control circuitry along with the feed network, account for major hardware cost. This report examines a number of antenna array configurations that use simpler feeds, simpler phase shifting and beam-steering control circuitry for realizing low cost phased arrays. Two lens configurations, one using diode strips (Radant) and another using voltage-controlled ferroelectric dielectrics are identified to have high potential for low cost phased arrays. Forroelectric dielectric lens may have further advantages of smaller thickness, simpler beam steering controls and lower costs.

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LOW COST PHASED ARRAYS

I. INTRODUCTION

One of the most versatile antennas used in radars aboard Naval ships is the phased array. Each radiating element of a phased array is normally associated with a phase shifter or a T/R module (in an active aperture phased array) with which the element phase can be varied through 360° degrees. The radiating elements are spaced nominally by $\lambda/2$ to avoid grating lobes. A typical phased array, with 1° pencil beam needs, an aperture of at least $50\lambda \times 50\lambda$ requiring some 10,000 radiating elements and phase shifters. The complexity of the corresponding feed network can increase rapidly with the size of the phased array. The phase shifters (or T/R modules) with their control circuitry along with the feed network account for the major hardware cost in a phased array antenna. This report examines a number of antenna configurations that provide simplification of the feed network, simplification of phase shifting and control circuitry for reducing cost of phased arrays. Other cost factors like software development are not included here. A large number of approaches and configurations were considered. A number of them were quickly rejected because they are either not practical or do not meet low cost goals of this study. Plasma Physics Division at NRL is pursuing an agile beam approach using plasma mirror [1]. If successful, plasma mirror could be one of the low cost approaches for phased arrays used for some applications. However, this approach is not included in this report because it is not a phased array. Only the phased array approaches which have potential for practical implementation and lower cost are included here.

One approach discussed here is that developed by Russians [2]. The Russian approach uses space feed, low cost phase shifters and row-column drivers. Another approach discussed here is the "RADANT" configuration. The "RADANT" lens provides a medium that is loaded with diodes which provide the needed phase shift by switching the diodes on and off. The diodes are switched by row-column controls. Other configurations discussed here employ ferroelectric dielectrics whose dielectric constant can be varied with applied D-C bias voltage. Finally, reflectarray configurations using the above mentioned approaches will also be discussed. The reflectarray configurations may have an advantage of lower volume (thinner), weight and cost compared to the lens configurations. It appears that the Radant and ferroelectric dielectric lens configurations are the most affordable phased arrays. Ferroelectric dielectric lens may have the additional advantage of smaller thickness and simpler beam steering controls compared to the Radant lens. Further work into the Radant lens and an extensive investigation into ferroelectric dielectric lens are being pursued by Radar Division at NRL.

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II. APPROACHES TO REDUCE COST OF PHASED ARRAYS

Three main items which contribute to the significant cost of the phased array are the feed network, the phase shifters and the beam steering control circuitry. For any affordable phased array, it is therefore essential to reduce the cost of these three items by providing a simpler feed, reducing the phase shifter's cost and using a simpler beam steering control.

A. Feed Simplification

A monopulse phased array antenna has a feed (beamforming) network system containing a transmitting channel and three receiving channels (Sum and two difference channels). The beamforming system can be fully constrained, using some sort of RF transmission lines, or free space with monopulse feed-horn at the focus. The beamforming system can account for a significant part of the overall cost of the phased array. A free space feed is much simpler and more cost effective. Advantages and limitations of free space feed and constrained beamformers are discussed below.

Fig. 1 shows a free-space feed for a lens. In the figure, separate phase shifter (which includes a driver) is shown behind each radiating element for clarity. However, in several approaches discussed in this report separate phase shifters and drivers are not used behind each radiating element. For space feed configuration spill-over sidelobes can be large for small antennas. They will have the approximate absolute gain of the feedhorn in the spill-over direction, which has to be compared with the absolute gain of the antenna. The free-space feed efficiency can be high, typically about -2dB. Monopulse pattern sidelobes are likely to be relatively large, perhaps -20dB, but fall-off rapidly. The antenna volume includes the focal region and hence is large.

Fig. 2 shows commonly used constrained beamforming network for a single row or a column. A large number of this type of networks are needed for a phased array. Compared to free-space beamformer, this is very complex and the beamformer efficiency is generally poor, particularly for the receive channels due to the insertion loss of transmission lines and connectors. The total antenna volume is minimal since the beamformer is substantially flat. Low sidelobe distributions can be separately optimized for the transmitting channel and the receiving channels.

For applications where ultra low sidelobes are not a requirement, using space feed will reduce the phased array cost.

B. Reduce Phase shifters Cost

The cost of the phased array can be reduced if the cost of the phase shifter is reduced by designing for minimum complexity, especially when a phase shifter is required behind

each radiating element. Other possibilities of reducing the cost of phase shifting include reducing the number of phase shifters, either by using bulk phase shifting, or sharing the phase shifters for more than one radiating element. One of these techniques will be incorporated in phased array configurations discussed later in this report.

C. Simpler Beam Steering Control

The cost of the phased array can also be decreased by reducing the complexity of the beam steering control circuitry. One approach is to reduce the number of drivers from nxm to n+m by controlling only rows and columns, where n is the number of columns and m is the number of rows in the phased array. In addition, reducing the power and complexity needed to control the drivers will further reduce the phased array cost. This simpler row-column beam steering control will be employed in the phased array configurations discussed later in this report. However, it should be noted that controlling the phase of whole column or row of phase shifters will introduce additional loss and phase shifting cost and the loss of individual radiating element amplitude and phase control. The last factor will limit the level of low sidelobes that can be achieved with the proposed row-column phase control technique. The technique will also limit the error correction possibilities. For the present study, it is assumed that ultra low sidelobes are not a requirement and row-column phase control can be used to reduce phased array cost.

III. DIFFERENT ARRAY CONFIGURATIONS

In this section several different phased array configurations which use the previously described cost reducing approaches will be discussed. The advantages and limitations of each configuration will be discussed.

A. Russian Approach

In a recent memo [2], David K. Barton described a Russian approach for low cost and high efficiency phased array design. According to Barton, the Russian approach is based on four major design features:

(1) Space-fed arrays are used, with multimode monopulse horn feeds to reduce spill over while retaining low sidelobes for transmit and receive sum channels and monopulse difference channels;

(2) Phase shifters are designed for minimum complexity, loss, and cost, using orthogonal circular polarizations for transmit and receive;

(3) Receiver protection is provided by low-noise electrostatic amplifiers which do not require solid-state limiters at their inputs;

(4) The arrays are designed for multiple-target tracking with relatively long dwells of medium- or high-PRF waveforms.

Barton states that no duplexer is necessary because the transmit and receive sum ports are isolated in the orthomode feed horn.

The key point in the Russian design is an array with phase shifters using Faraday rotator devices capable of producing a maximum of 720° of phase shift. Each driver commands either a full row or a column reducing the number of drivers. Row and column commands are applied to separate coils as shown in Fig. 3. The phase shifters are reciprocal for an orthogonal circularly polarized signal. Mr. Barton quotes the phase shifter price as $20 and the loss as 0.8dB. If these quoted values can be achieved here in the U.S.A., the Russian approach should be a prime candidate for low cost phased arrays. However, the following points should be considered before one gets too enthusiastic about the Russian approach.

Russian approach still uses a separate phase shifter at each radiating element. Each phase shifter uses two separate coils in series, each producing 360° for a total of 720°. So one expects the losses to be twice as much as that of a single phase shifter producing 360° phase shift. So, the phase shifter loss of 0.8dB seems very unrealistic. Also, it is not obvious why the Faraday rotator phase shifter will cost only $20 when other phase shifters cost, at least an order of magnitude, more. In addition, the success of row-column commands depends on the similarity of the phase shifters (the assumption is that they are precisely the same). Unless an inordinate selection process, incompatible with $20 cost, is undertaken in selection and arrangement of the phase shifters, the variance would be expected to be quite large. This would create significant sidelobe levels. The final point is the use of opposite circular polarization for transmit and receive. With circular polarization for any one sense of transmitter polarization, the echo signal typically is about equally divided between right- and left-circular polarization [3]. However, it is observed that opposite-sense polarization predominates in the echo signal from rain drops [3]. This phenomena may result in 3dB more return from rain clutter compared to the target return. Any other ramifications of using circular polarization should also be considered.

For the above stated reasons, it is not clear if the Russian approach is the right approach to be considered for low cost phased arrays, even though further investigation may be warranted.

B. RADANT Approach

The Radant lens is a novel antenna, with low-cost means of implementing single or dual-plane electronic scanning. The Radant lens design reduces many fabrication problems that increase cost and transmission loss in the conventional implementation, namely the discrete element and phase shifter approach that has been almost universally applied to implement high performance electronically scanned phased arrays. Specifically, the Radant lens eliminates all packaging, all connectors and transmission lines associated with discrete phase shifters. It also reduces greatly the control circuitry, drivers and connecting leads. Therefore, the Radant lens has the potential for low cost, low-weight implementation.

The basic principle on which the Radant lens operates has been demonstrated earlier by Radant Technologies, Inc. [4] under a contract to Rome Laboratory. The Radant lens is a lens constructed from a diode controlled artificial dielectric as shown in Fig. 4. In the lens the electric field is constrained to propagate between parallel metal plates. In between the plates, the artificial dielectric is constructed from strips of metal with cross connected diodes on a dielectric support layer, shown in light gray in Fig. 4. The principle of operation is that the phase shift through this artificial dielectric medium changes when the diodes in one strip are turned on or off. The amount of metalization controls the amount of phase shift per diode strip. Phase shifting results from selectively switching between the two diode states via some digital bias control circuitry. The phase delay achieved is modulo 360°. The simplest configuration is an E-plane scanning lens in which beam steering results from a linear phase gradient (along the E-plane dimension). A simple Radant lens provides one dimensional electronic beam scanning. By restricting the scan action of a lens to a single plane, a great simplification in the bias circuitry is achieved since the individual diodes need not be addressed independently. This reduces the complexity of the driver and facilitates its location exterior to the lens. Two dimensional scanning can be achieved by cascading two Radant lenses or using one Radant lens in a hybrid configuration.

Fig. 5 shows cascading of two spatially orthogonal Radant lenses. The first one provides azimuth scan of a horizontally polarized wave. A 90° passive polarization rotator then rotates the electric field to become vertically polarized. The second lens then provides the elevation scanning of the vertically polarized wave. A space feed can be used, as shown in Fig. 6, with the cascade (dual) lens configuration. In the dual lens configuration, row-column phase controls can be used to correct the spherical errors due to the space feed, even though this phase correction is not exact. Spherical phase-error corrections for an offset feed configuration is not possible with row-column phase controls. So, offset feeding of the Radant lens is not recommended.

Another method of achieving two dimensional scanning uses a hybrid technique in which a conventional discrete, linear array of phase shifters provides scanning in one plane and the Radant lens provides the scanning in the other plane. Fig. 7 shows a hybrid configuration. The illuminator is a stacked slotted waveguide array with the slots in the narrow wall of the waveguide. Each waveguide is fed through a phase shifter at its input. The waveguide array radiates a horizontally polarized wave. Elevation scanning is achieved with these phase shifters. Azimuth scanning is obtained by placing a Radant lens in front of the waveguide array (illuminator). The hybrid configuration is probably the most economical means of providing two dimensional scanning using Radant technology. However, high power Radar applications, demand high power phase shifters which are difficult to obtain. Furthermore, these phase shifters must be nonreciprocal, a fact which causes eclipsing. In addition, the instantaneous bandwidth is limited due to the slotted waveguide array.

As stated earlier, Radant Technologies, Inc. built a 2'x 2' Radant lens using hybrid configuration for Rome Laboratories and reported good performance results [4]. NRL borrowed that lens from Rome Labs and repeated the performance tests and found them to be as good as those reported earlier [4]. A recent study by NRL [5] indicated that the hybrid approach of combining a slotted waveguide array with Radant lens is a low cost approach for phased array which can meet the requirements of ship self-defense. Since then, a slotted waveguide array was acquired which was a modified version of a production series (AN/TPQ-36) built by the Hughes Aircraft Company. The modified version used high-power phase shifters and a monopulse feed network, and can phase scan in the azimuth plane. Recently, a contract was awarded to procure a Radant lens which will be added to the front of waveguide slotted array to obtain scanning in the vertical plane. The cost of this hybrid approach is considered to be quite affordable compared to a full-fledged phased array using either phase shifters or T/R modules behind each radiating element.

The Radant lens antenna cost is low relative to a discrete element array because of the elimination of the separate packaging, connectors, assembly, and radiating elements. The lens itself is the antenna, and is fabricated from long strips, of which there are only two or three different types. In production, the diodes are soldered onto these strips with automated equipment. Furthermore, the control circuitry for the Radant Lens antenna is vastly simpler than a discrete phased array. For an N-row and M-column element array, the Radant Lens requires only N+M row-column commands, rather than NxM commands associated with a conventional 2-dimensional scanned phased array.

Radant Lens technology is being advanced in France by Thompson-CSF. They are using this technology in producing RBE-2 radar for the French Rafale Fighter Aircraft. They use dual lens

system to scan in azimuth and elevation. A slotted waveguide array is used as the illuminator to the Radant lens. With this type of illuminator, monopulse capability exists only in one plane.

C. Approaches Using Ferroelectric Dielectrics

The major feature of antennas which use ferroelectric materials is the change of permittivity with an applied control voltage. Two possible configurations, one a travelling wave type and another a lens type antenna, will be discussed.

1. Travelling Wave Configuration

Fig. 8 shows one of the possible antenna configurations using ferroelectric dielectrics. The antenna consists of a ground plane covered with a slab of ferroelectric material. The top of the ferroelectric material is covered with a conducting sheet with slots. The slots act like radiating elements. A line source feed of arbitrary configuration can be used as the input. The slots are designed such that no grating lobes are formed. The thickness of the dielectric slab is chosen to propagate only a dominant mode. The electric field is normal to the ground plane, as shown. The radiating beam direction, when no D.C. bias is applied to the structure, is determined by the slot spacing and dielectric constant of the slab. Now, if the D.C. bias is applied between the ground plane and the top conducting strips the dielectric constant of the ferroelectric dielectric will change, consequently, the direction of the radiating beam will change. So, by changing the applied bias voltage, the beam can be scanned in the elevation. The beam can be scanned in the azimuth by scanning the input line source feed. It may be noted that the input line source can be a linear array with a phase shifter at each element in the linear array. A similar structure was proposed by Hughes Aircraft Company [6].

This travelling wave configuration using ferroelectric dielectric material can be a very low cost phased array because of the ease of antenna construction and much simpler phase control (only one D.C. bias voltage need to be controlled). However, there is one main drawback for this approach. The existing ferroelectric materials are very lossy. One can expect dielectric losses of about 1dB per wavelength at X-Band. If an antenna length of about 50λ (for a one degree beam) is required, the losses in the material can be considerable when the signal needs to propagate through the material for the whole 50λ length as it would be for this travelling wave antenna configuration. The losses can be reduced by subarraying; however, the number of line sources, the corresponding phase shifters and hence the complexity increases with the number of subarrays. In addition, power absorption in the load termination, instantaneous and agility bandwidth limitations are also problems. These are not discussed in detail here because the practicality of the travelling wave antenna configuration using ferroelectric dielectrics is mainly limited by the losses in the material. Our

recent enquiry into those losses [7] indicated that the possibility of developing ferroelectric materials with losses low enough to be useful for travelling wave antenna is remote. Also, our recent communications with Hughes Aircraft company indicated that they have modified their task on travelling wave type ferroelectric dielectric antenna for the same reason and are working on improving ferroelectric materials. At this time, they are not very optimistic about producing ferroelectric materials with very low losses and useable tunability. For these reasons, our efforts will be concentrated more in developing a ferroelectric dielectric lens, which will be discussed in the next section.

2. Lens Configuration

Fig. 9 shows a dielectric lens made up of dielectric slabs sandwitched between conducting plates. Dielectric slabs are made-up of ferroelectric material whose dielectric constant can be changed by applying and varying the D.C. electric field (D.C. voltage sources V_1, $V_2 \ldots V_n$ are used for this purpose, as shown in Fig. 9). If a plane wave is incident on one side of the lens with electric field $\bar{E}$ normal to the conducting plates, the beam coming out on the other side of the lens can be scanned in the E-plane if a linear phase gradient is introduced along the E-plane direction by adjusting the voltages V_1, V_2, $V_3 \ldots V_n$. The corresponding dielectric constants are shown as ϵ_1, ϵ_2, $\epsilon_3 \ldots \epsilon_n$.

Assuming some typical values of 80 to 100 for the range of dielectric constants and a loss tangent of 0.005, it can be shown that the lens thickness needed to produce a maximum phase shift of 360° is about λ_0 and lens losses are about one dB at X-band frequency. Therefore, a lens which uses ferroelectric dielectrics is quite practical and can be used as a low cost phased array. The appearance of the lens is similar to a Radant lens, except that the ferroelectric lens thickness can be about λ_0 whereas the Radant lens thickness is 3 to $4\lambda_0$. In addition, the number of phase controls are less compared to that of a Radant lens. To avoid higher order modes and match the lens surface to free space on both sides, a configuration shown in Fig. 10 can be used. In this configuration, the ferroelectric slab thicknesses are chosen to be less than $\lambda/2$ to avoid higher order modes and quarter wave transformers are utilized for matching to free space.

Single plane scanning (in the E-plane) can be achieved using one lens. Scanning in two planes can be achieved by using two lenses with a polarizer between them, similar to Radant approach, as shown in Fig. 11.

The lens or lenses can be fed by a planar array (for example, a slotted waveguide array). A combination of a slotted waveguide array with phase shifters and the lens proposed here can be used as an antenna (similar to a Radant lens as shown

in Fig. 7) which may result in a phased array with lowest cost, less weight and less volume and can scan in two planes.

D. Reflectarrays

Fig. 12 illustrates a basic reflectarray configuration. The reflectarray consists of a space-feed, the array surface, phase shifters (either individual or bulk type) and short circuit terminations. The signal from the space-feed is picked up by the array face, goes through the phase shifters, reflects back from the shorts, goes back through the phase shifters, and radiates from the array surface into free space. Since the signal goes through each phase shifter twice, the actual phase setting of the phase shifter is one half of the total phase setting needed to scan the beam. Therefore, the maximum phase shift needed is modulo 180° instead of modulo 360°. This observation will result in reduced thickness for the lens and simpler phase shifters, resulting in lower cost with reduced weight antenna compared to a regular lens configuration. Even though the phase shift needed is halved, the loss through the phase shifters (or reflectarray) is not reduced because of the round trip travel of the signal through the phase shifters. Another point to be noted is that the phase shifter bit size needed may have to be increased by one bit for reflectarray configurations to keep the same quantization errors as the regular configuration. A brief description of different types of reflectarrays are given below.

1. Reflectarray using Russian Approach

Fig. 13 shows the Reflectarray configuration using the Russian approach of using low cost Faraday rotator phase shifters. The configuration is similar to the regular approach used by the Russians, as shown in Fig. 3, except that the phase shifters are terminated with a short circuit, no radiating elements are needed and the total phase shift of each phase shifter is 360° (two 180° in series) instead of 720°. Otherwise, the general comments stated at the beginning of the section on reflectarrays will also apply to this configuration.

2. Radant Lens Reflectarray

Fig. 14 shows the Reflectarray configuration using two Radant Lens panels. The configuration is similar to the regular Radant Lens except that the second panel is covered with a conducting plate and the panel widths are about one half because they need to introduce a maximum phase shift of only 180° instead of 360°. Otherwise, the general comments stated at the beginning of the section on reflectarrays will also apply to this configuration.

3. Ferroelectric Dielectric Lens Reflectarray

Fig. 15 shows a Reflectarray configuration which uses two panels of Ferroelectric dielectric lenses. The

configuration is similar to regular ferroelectric dielectric lens which scans in two dimensions, as shown in Fig. 11, except that the second panel is terminated in a conducting sheet and the maximum phase that needs to be introduced by each panel is 180° instead of 360°. Otherwise the general comments made at the beginning of this section on reflectarrays will also apply for this configuration except that the effect due to quantization phase errors does not exist here because the phase is controlled by analog D.C. bias voltage.

IV. CONCLUSIONS AND RECOMMENDATIONS

In a phased array antenna, the phase shifters (or T/R modules in active aperture phased arrays) with their beam steering control circuitry along with the feed network account for the major hardware cost. This report examined a number of phased array configurations that use simpler feeds, simpler phase shifting and beam steering control circuitry for realizing low cost phased arrays. However, the approaches discussed here are incompatible with ultra low sidelobe requirements. Hence, the low cost phased arrays proposed here will be useful in applications where the sidelobe requirements are modest. Two lens configurations, one using diodes (Radant lens) and another using voltage controlled ferroelectric dielectrics have high potential for low cost phased arrays. Ferroelectric dielectric lens may have further advantages of smaller thickness and simpler beam steering control compared to the Radant lens. Reflectarrays using these technologies may further reduce cost, weight and volume. Further work into the Radant lens and extensive investigation into ferroelectric dielectric lens are being pursued at Radar Division, Naval Research Laboratory.

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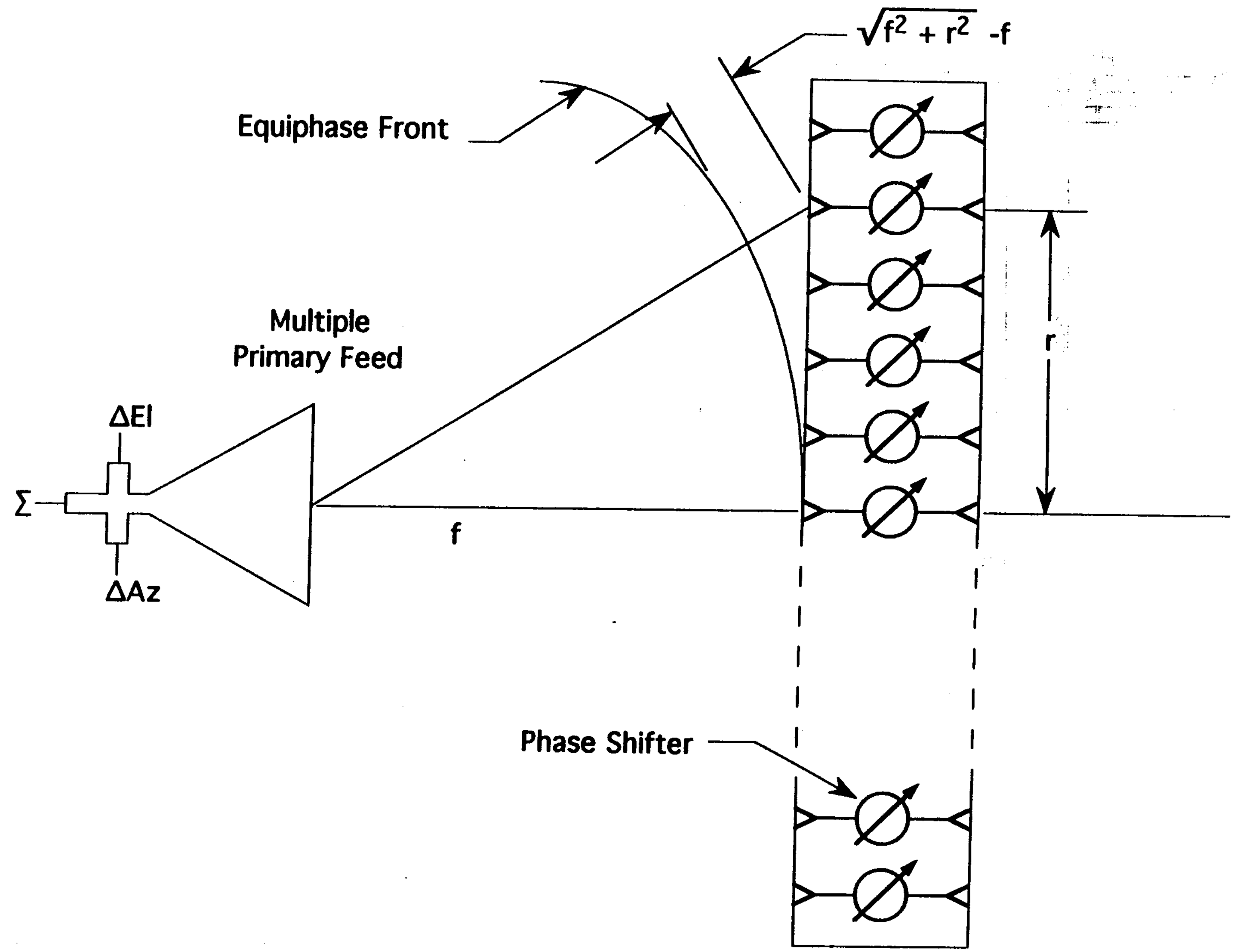

FIG. 1. FREE SPACE FEED CONFIGURATION FOR A LENS ANTENNA

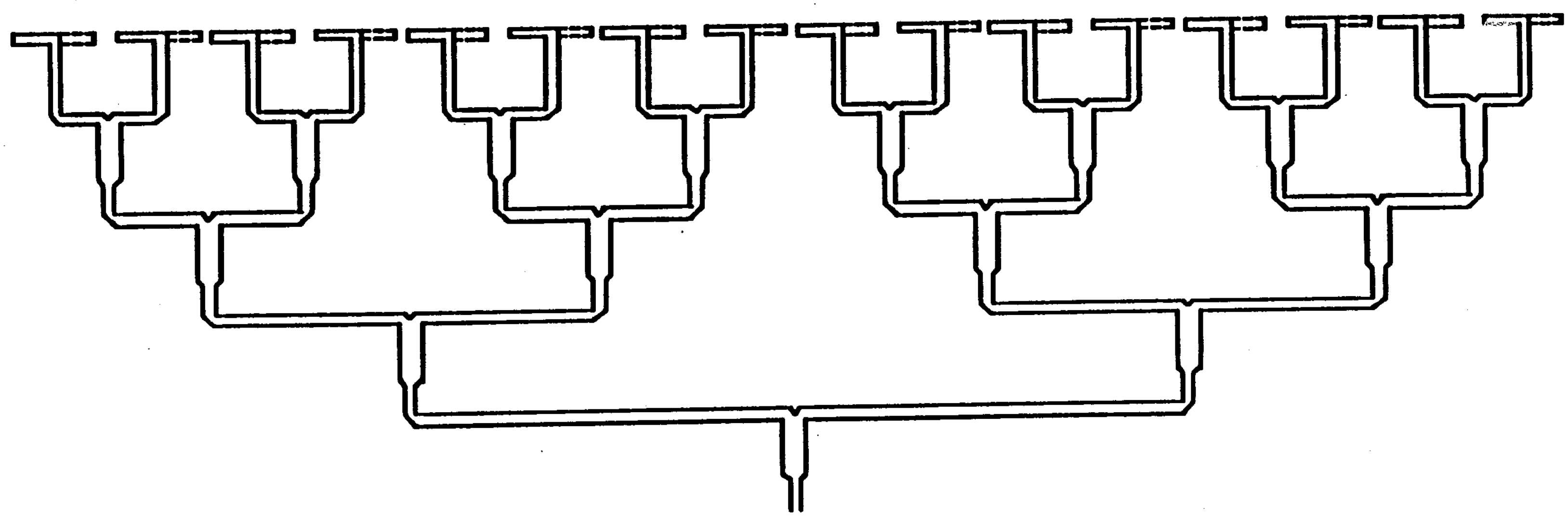

FIG. 2. TYPICAL CONSTRAINED FEED NETWORK FOR ONE ROW OF A PHASED ARRAY

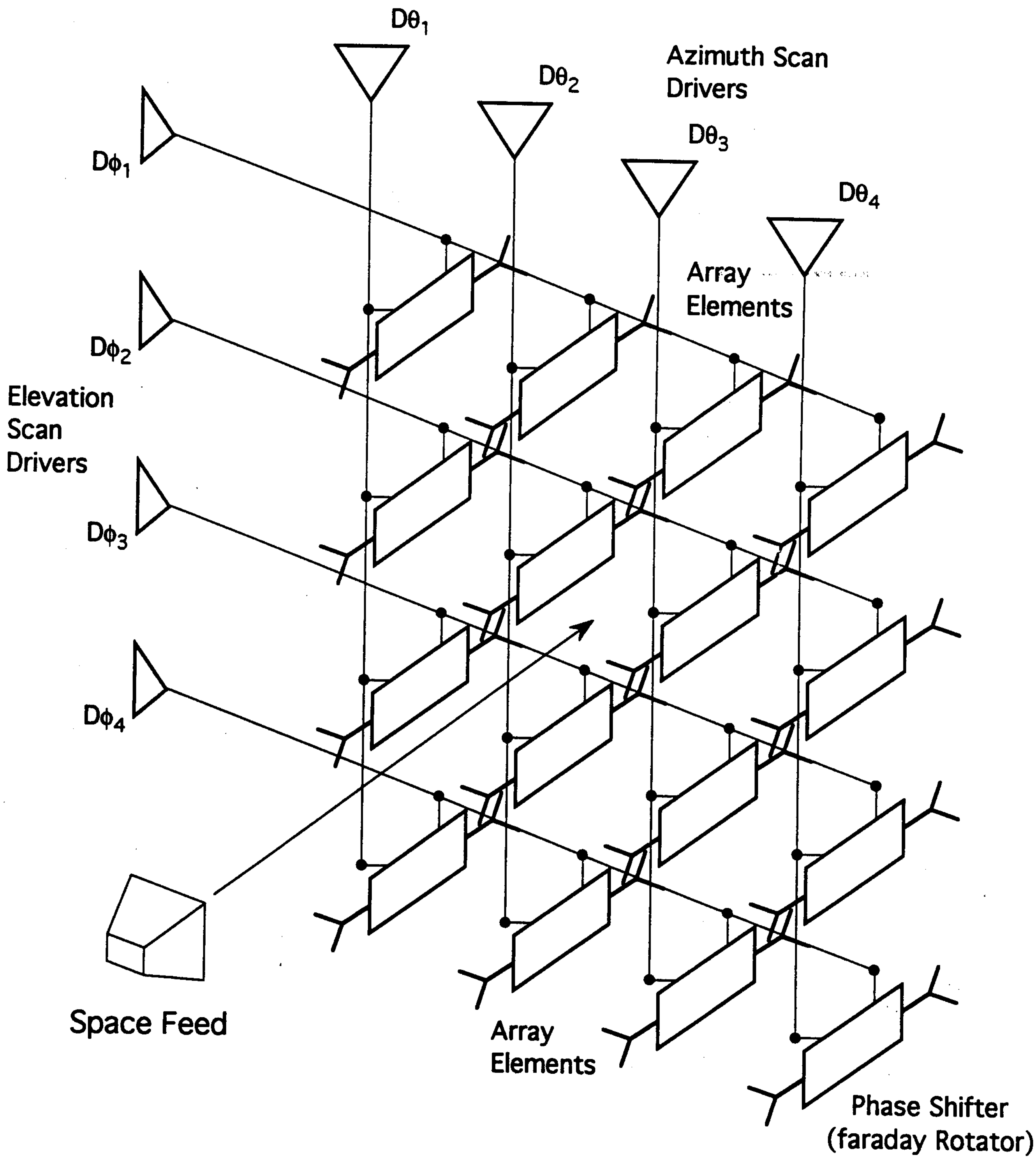

FIG. 3. Configuration of Phased Array Using Russian Approach

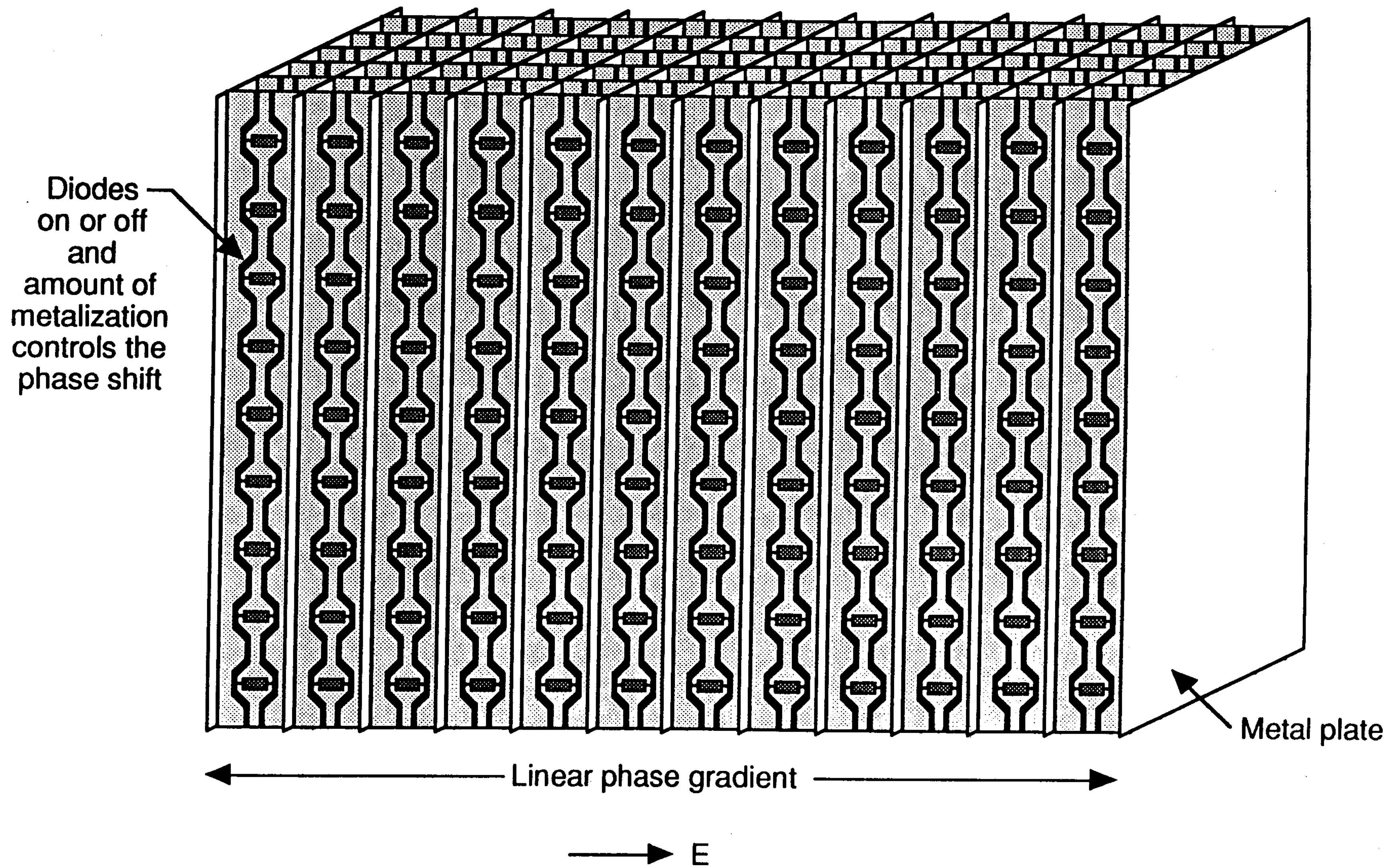

FIG. 4. RANDANT LENS CONFIGURATION

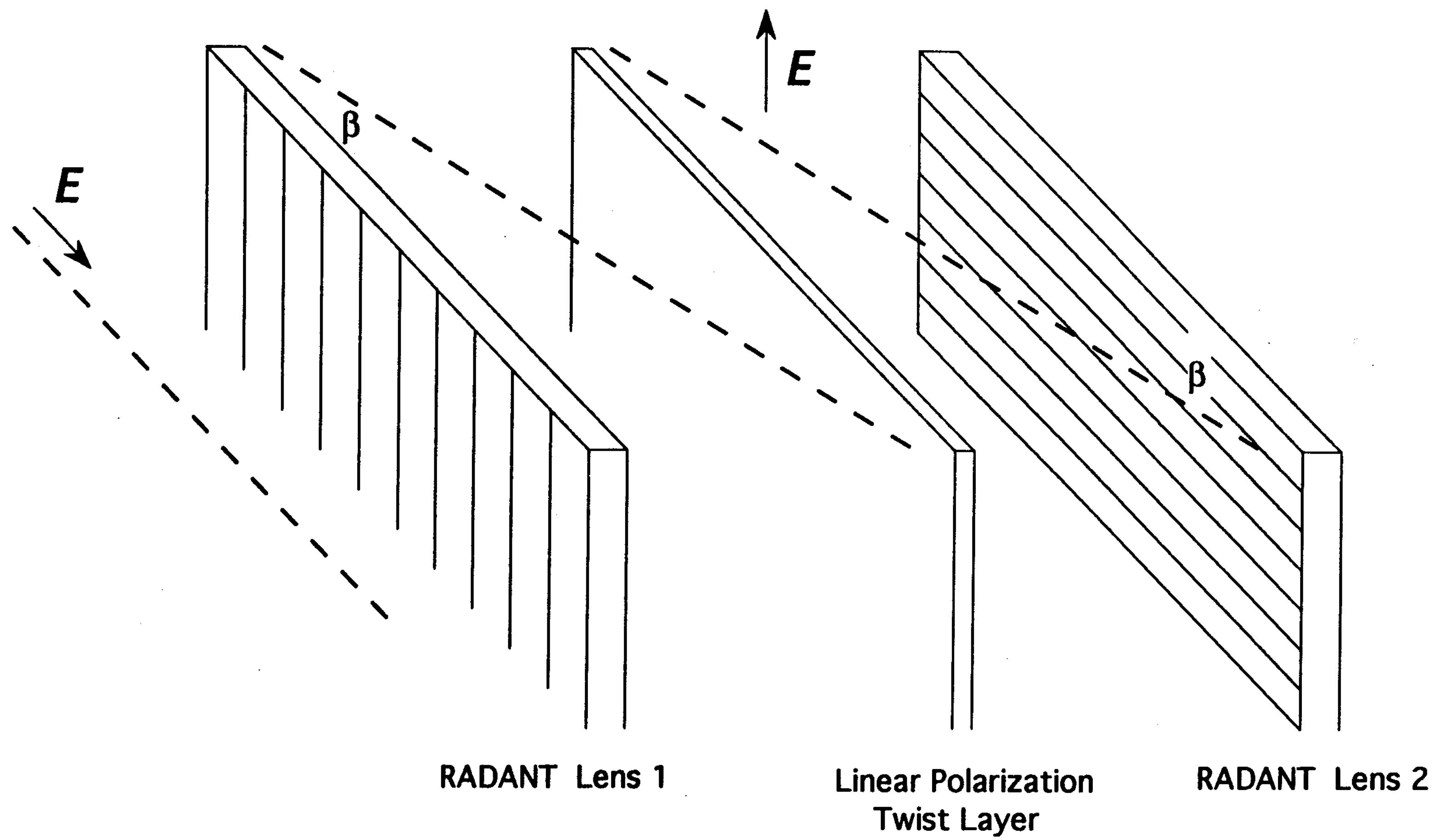

FIG. 5. DUAL LENS CONFIGURATION FOR TWO DIMENSIONAL SCANNING USING TWO RADANT LENSES

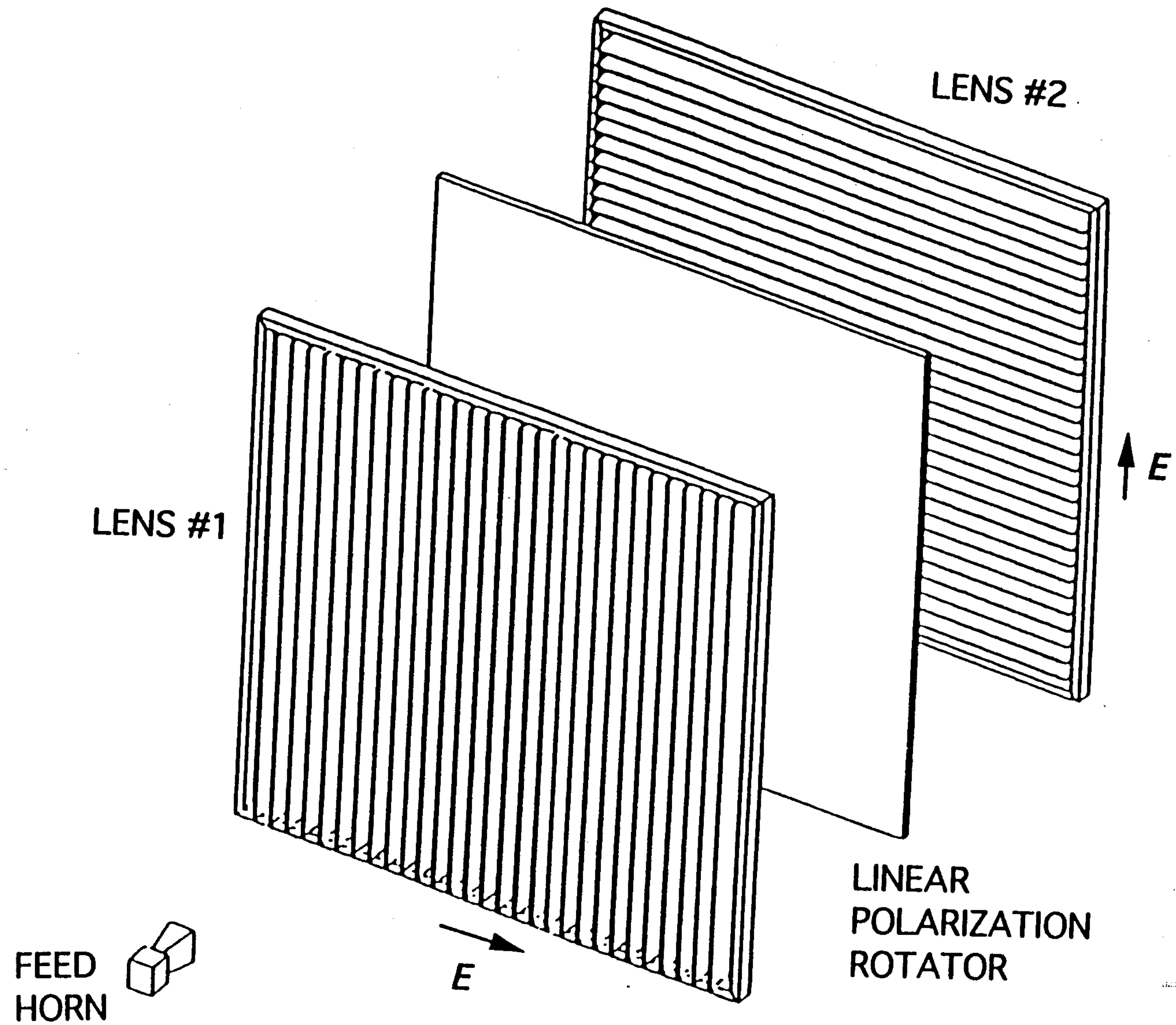

FIG. 6. DUAL RADANT LENS CONFIGURATION WITH SPACE FEED

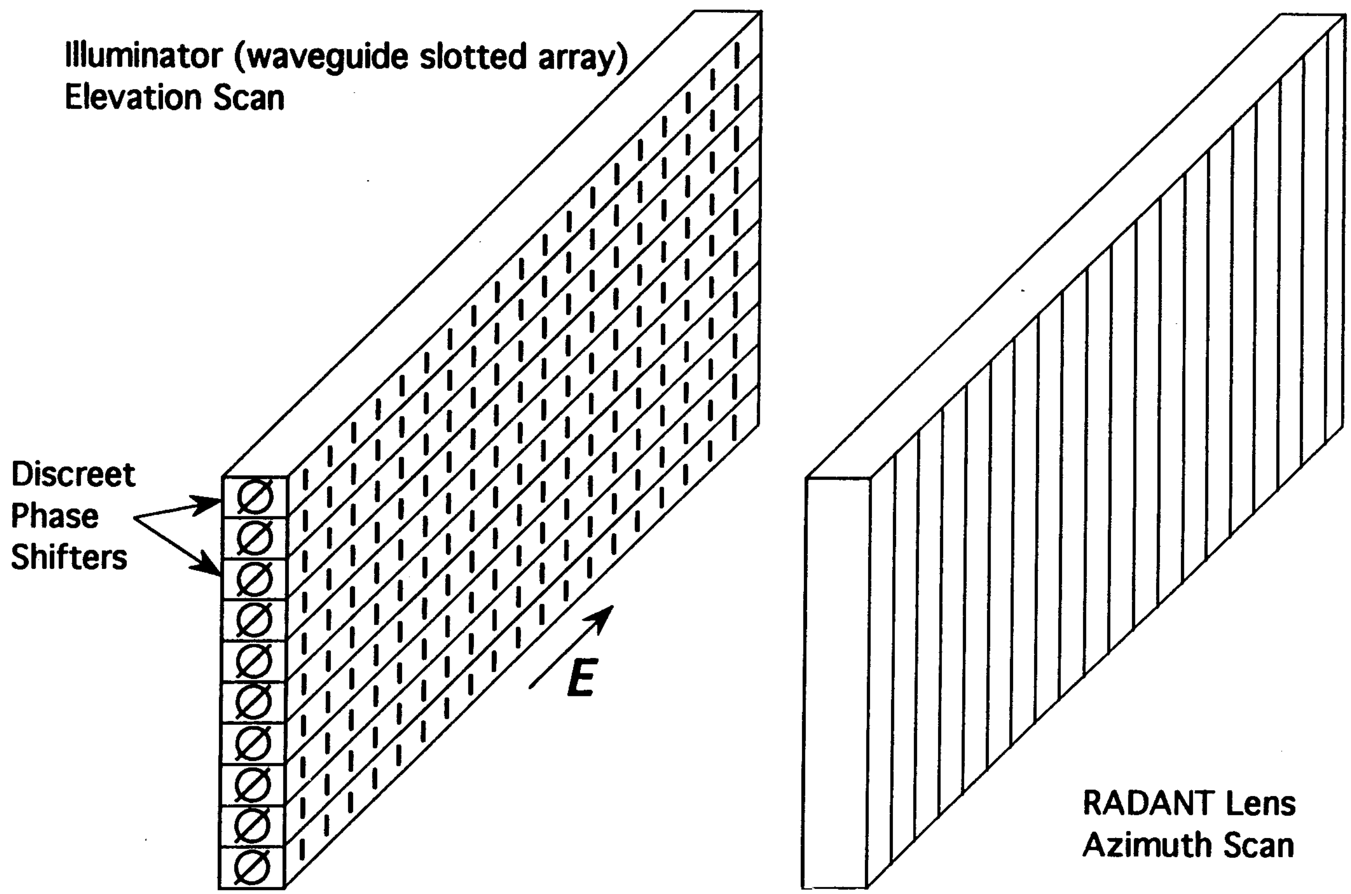

FIG. 7. HYBRID PHASED ARRAY CONFIGURATION FOR TWO DIMENSIONAL SCANNING USING A RADANT LENS

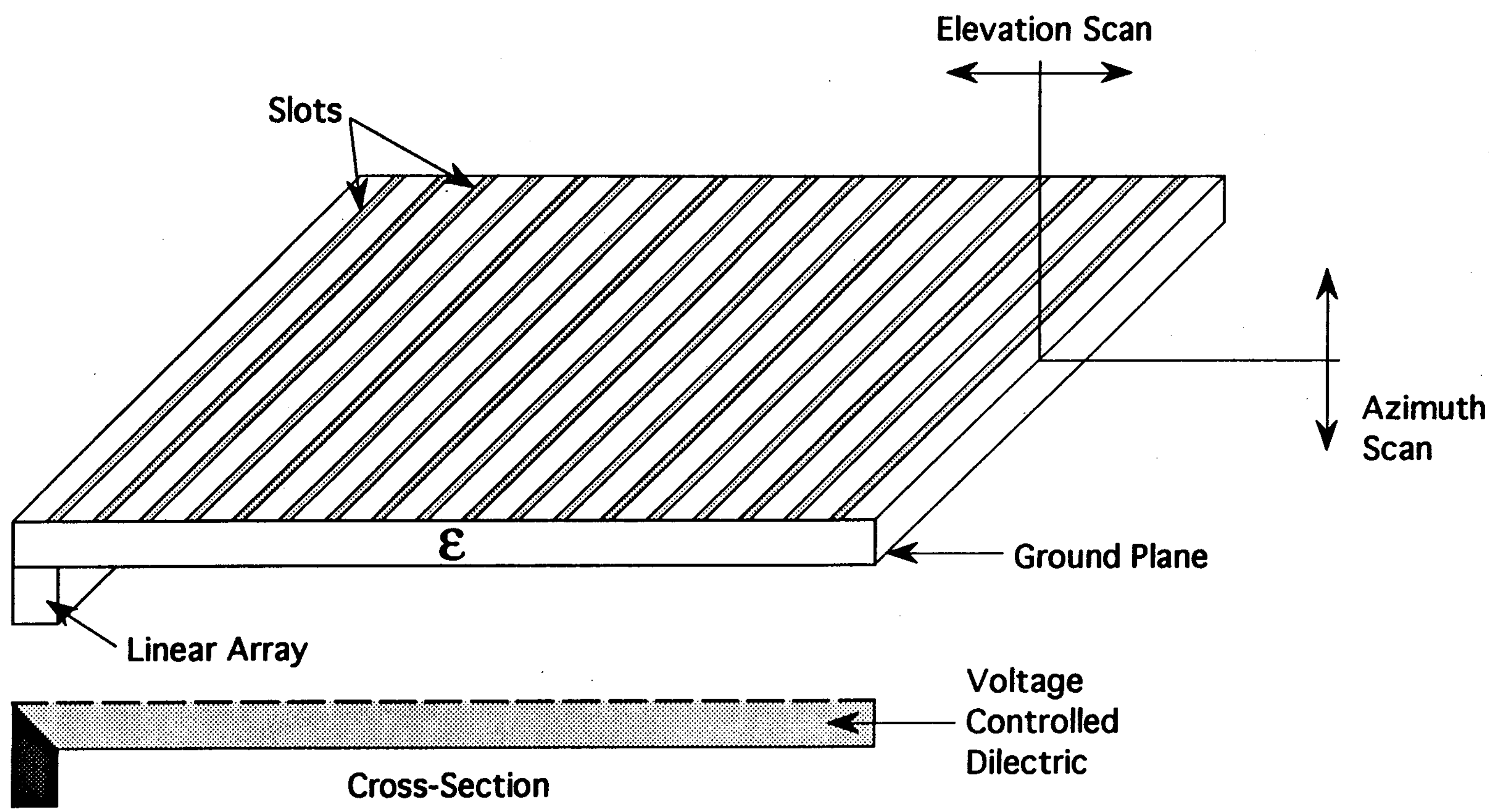

FIG. 8. HYBRID SCANNING PHASED ARRAY USING TRAVELING WAVE ANTENNA WITH VOLTAGE CONTROLLED DIELECTRICS

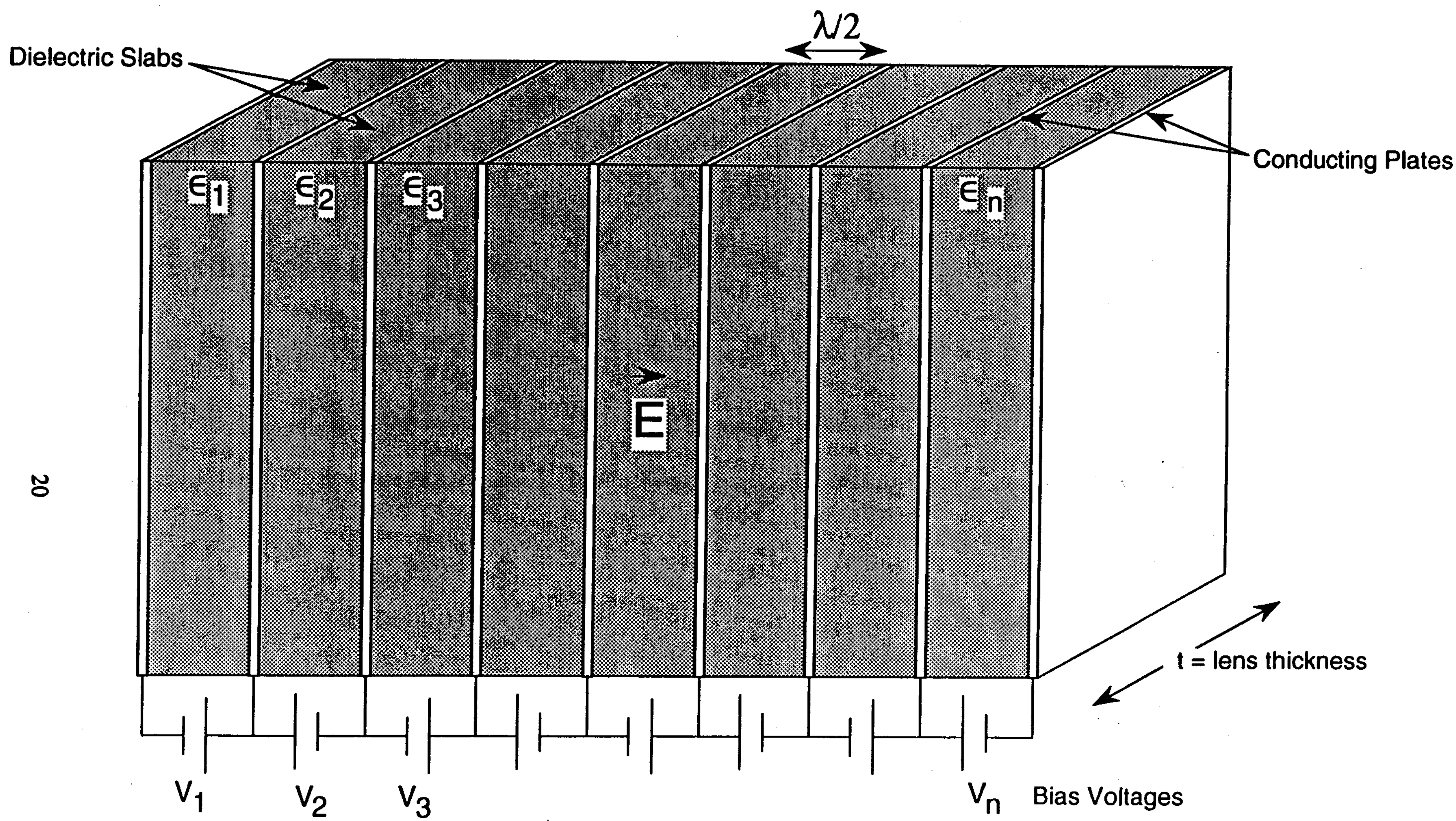

FIG. 9. BASIC VOLTAGE CONTROLLED DIELECTRIC LENS CONFIGURATION

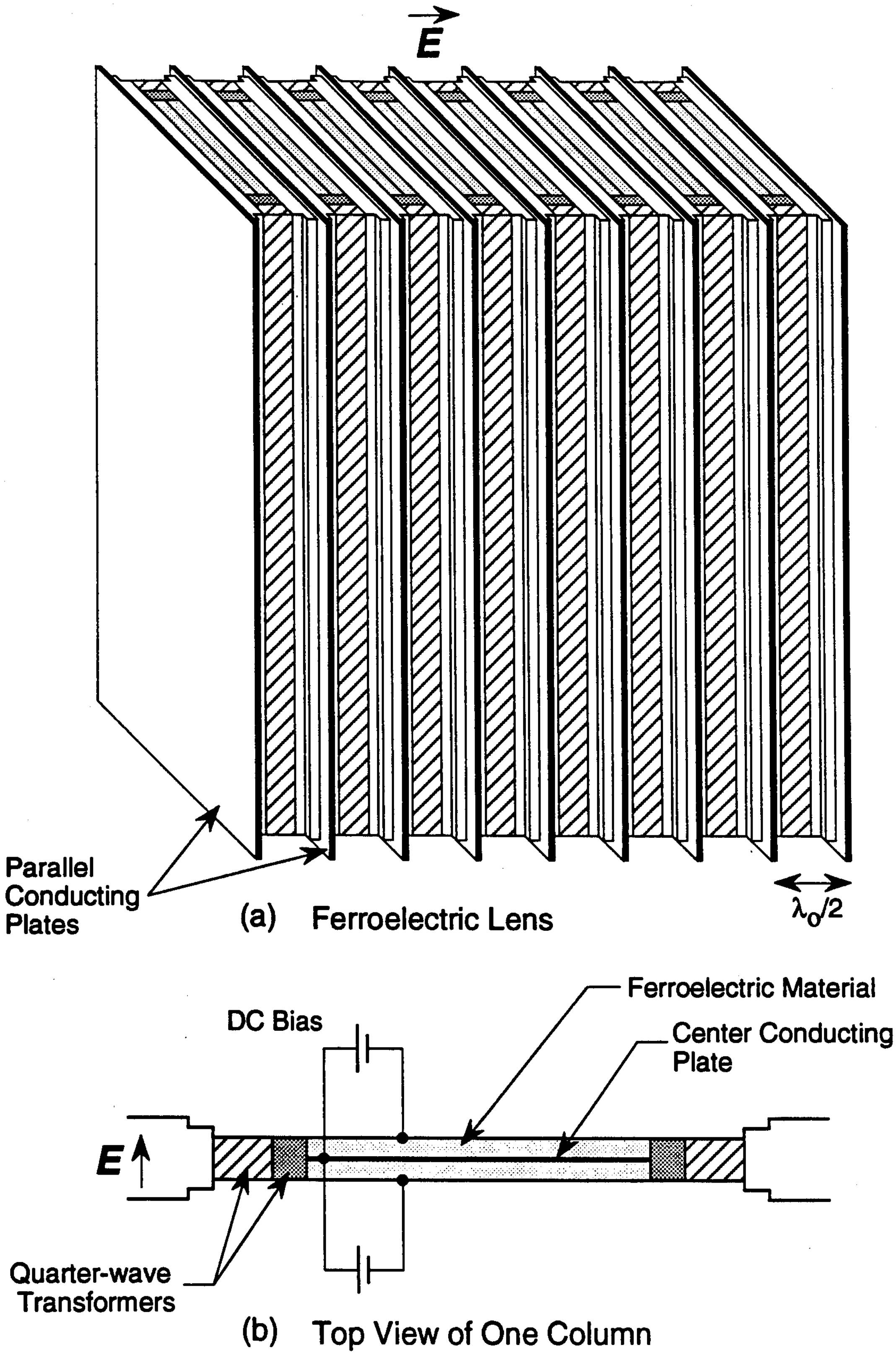

FIG. 10. MORE PRACTICAL CONFIGURATION OF VOLTAGE CONTROLLED FERROELECTRIC LENS

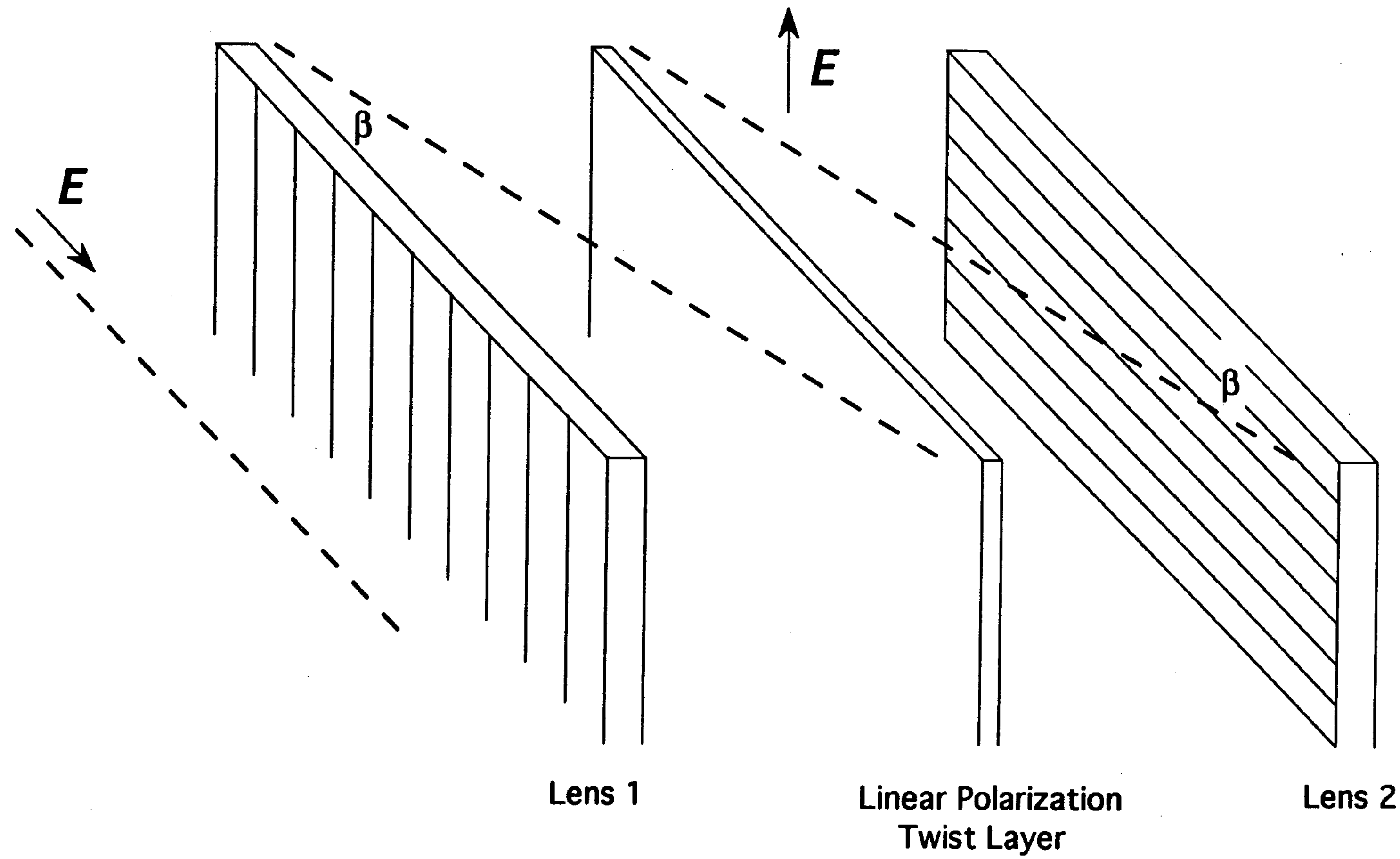

FIG. 11. DUAL LENS CONFIGURATION FOR TWO DIMENSIONAL SCANNING USING TWO VOLTAGE CONTROLLED FERROELECTRIC LENSES

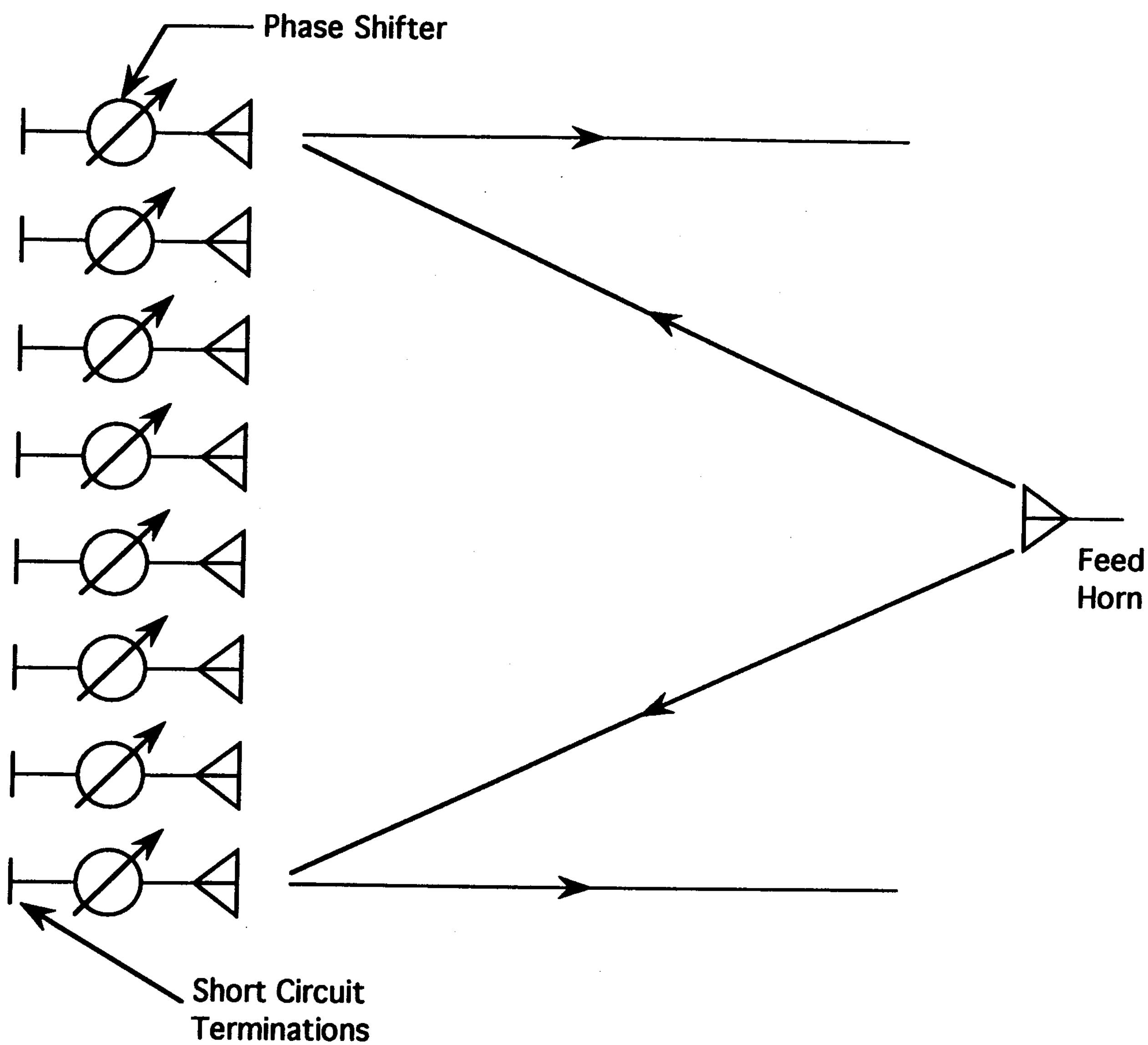

FIG. 12. REFLECTARRAY CONFIGURATION

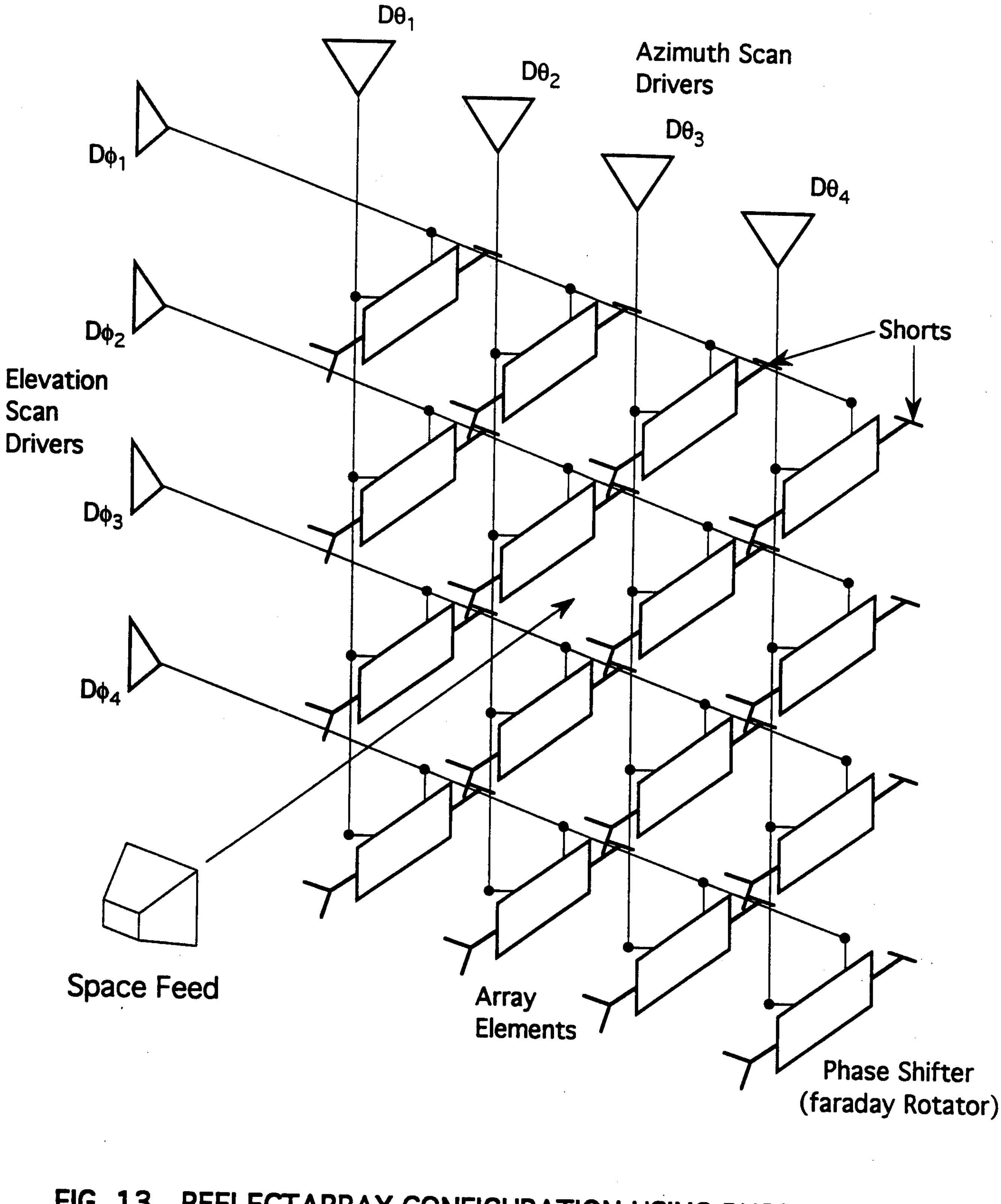

FIG. 13. REFLECTARRAY CONFIGURATION USING RUSSIAN APPROACH

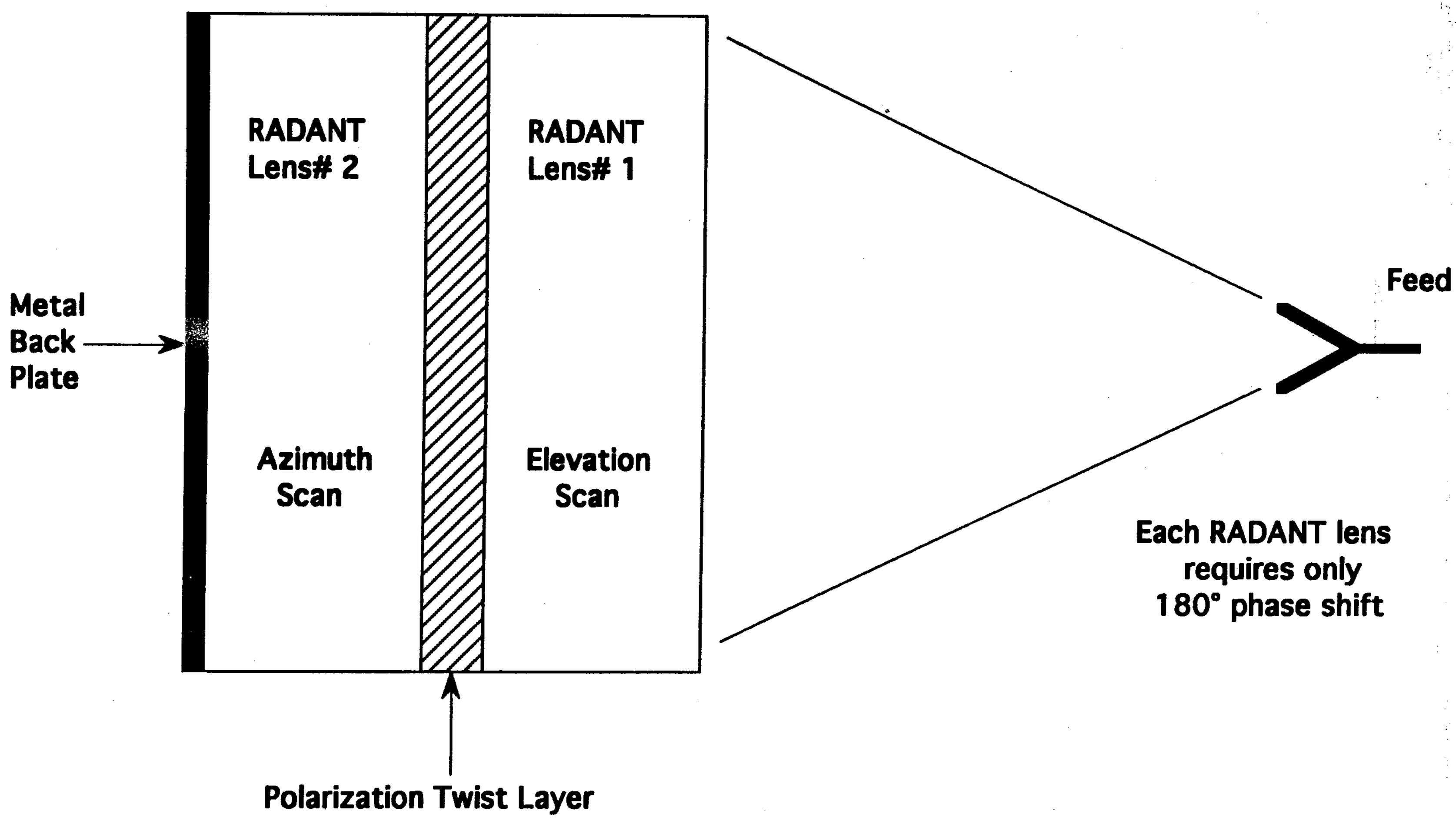

FIG. 14. REFLECTARRAY USING TWO 180° RADANT LENSES

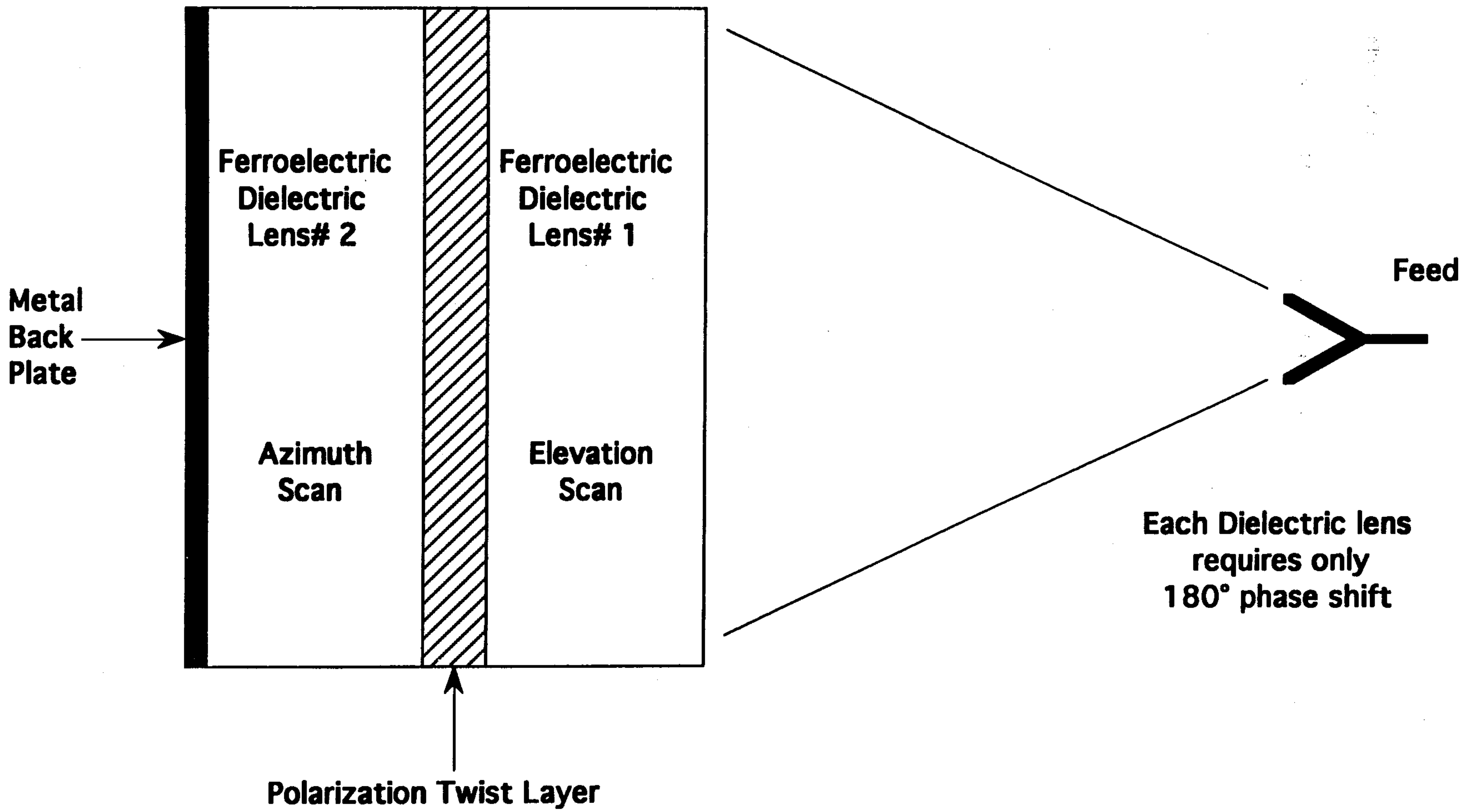

FIG. 15. REFLECTARRAY USING TWO 180° FERROELECTRIC DIELECTRIC LENSES